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Characterization of Ti-6%Al-4%Vand VascoMax C-350

A. J. Sunwoo

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Anne J. Sunwoo

Ti-6%Al-4%V Alloy

The α-β Ti-6% Al-4% V (Ti64) alloy can be heat treated to meet the specified requirements of the applications. The as-received material from SLAC was given a solution heat treatment (SHT) to have a good strength and ductility combination. The SHT was done at 200˚C below the Beta transus of 990˚C for 15 min and air-cooled to 20˚C. The designed microstructure consists of β phase precipitates within the α phase matrix. The characterization of the as-received Ti64 alloy sheet microstructure reveals equiaxed, 10 µm-sized grains on the flat surface and finer, 8 µm-sized grains in the through thickness. Figures 1and 2 show the microstructure of the alloy. The typical Ti64 microstructure is lamellar structure, consisting of alternating α and β phases. In order for the alloy to have the micron sized, equiaxed grains, it had to undergo extensive wrought processing. The Vicker's microhardness numbers (VHN) showed that the slightly larger grained flat surface had a higher averaged value than the through thickness; 33 kg/mm^2 vs. 30 kg/mm^2. The residual effect of wrought processing is still present even after the SHT to cause the small difference in the hardness values.

The results of tensile tests conducted at LLNL and at BNL are given in Tables 2 and 1 in Appendices 1 and 2, respectively. The effects of the irradiation dosage damage on the tensile properties of the Ti64 are presented in Appendix 2. The as-received tensile specimens are not the standard specimens for testing. As shown in Attachment, Figure 1, only the 6 mm length is used in the reduced gage section of the specimens. As a result, a small change in the gage length will translate to a higher percentage change in elongation, giving higher elongation values than using the 30 mm length of the specimen. Since most of the deformation is concentrated in the reduced gage section, the present results are more accurate measurement of ductility. The Ti64 specimens failed in the center of the gage section.

The Ti64 alloy contains extra low interstitials (ELI). There are an advantage and a disadvantage to having ELI. The advantage is that the alloy can exhibit good ductility since there is no effective deformation hindrance to mitigate the deformation twinning. The strength of the alloy is predominantly obtained from fine, equiaxed α grains. Given only the SHT, the alloy exhibits an adequate strength and ductility combination. The disadvantage of ELI is that the Young's modulus is sensitive to composition and heat treatment. The present alloy displays slightly lower Young's modulus values than the reported value of 108 GPa with the comparable SHT [1]. If needed, higher Young's modulus and strength can be obtained with subsequent aging treatment.

The fracture surfaces of the specimens suggest ductile, dimple failure. Figure 3 shows the representative fracture characteristics of SHT Ti64. The cross-sectional view of the broken specimen has the appearance of extensive deformation prior to fracture (see Fig. 3a). The contribution of microstructure is clearly seen in the fracture surface, where the larger dimples represent the α phase since the dimple sizes are equivalent to the grain size. The smaller dimples are surmised to be β precipitates. In addition to dimples, the fracture surface contained some sheared grains, indicated by the arrow in Figure 3b. It is inferred that since the deformation mechanism is twinning, it could be the twin interface separation.

VascoMax C-350

The VascoMax C-350 maraging steel is very high strength material that was designed to exhibit 2.4GPa strength at the peak heat-treated condition. The as-received specimens were SHT to the martensitic condition. In this particular condition, the steel does not exhibit its high steel or work hardening behavior. Tensile tests showed a small difference between the yield strength and UTS values. Another uniqueness of this steel is that there is a significant difference in elongation and reduction of area values. It is known that with the high strength materials, they tend to be less ductile. Instead, the reduction of area value is extremely high.

The tensile properties of the as-received VascoMax C-350 are compared with the manufacture's technical datasheet; see Tables 2 and 3, in Attachment. Given the unknowns of strain rate, specimen geometry, and heat treatment condition, the UTS, elongation and reduction of area values were comparable. The as-received specimens were tested at the strain rate on the order of 10^{-3}/s, which is slightly higher than the standard rate of 10^{-4}/s. If the steel is rate sensitive, then the differences in the Young's modulus, yield strength, and work hardening behavior are expected.

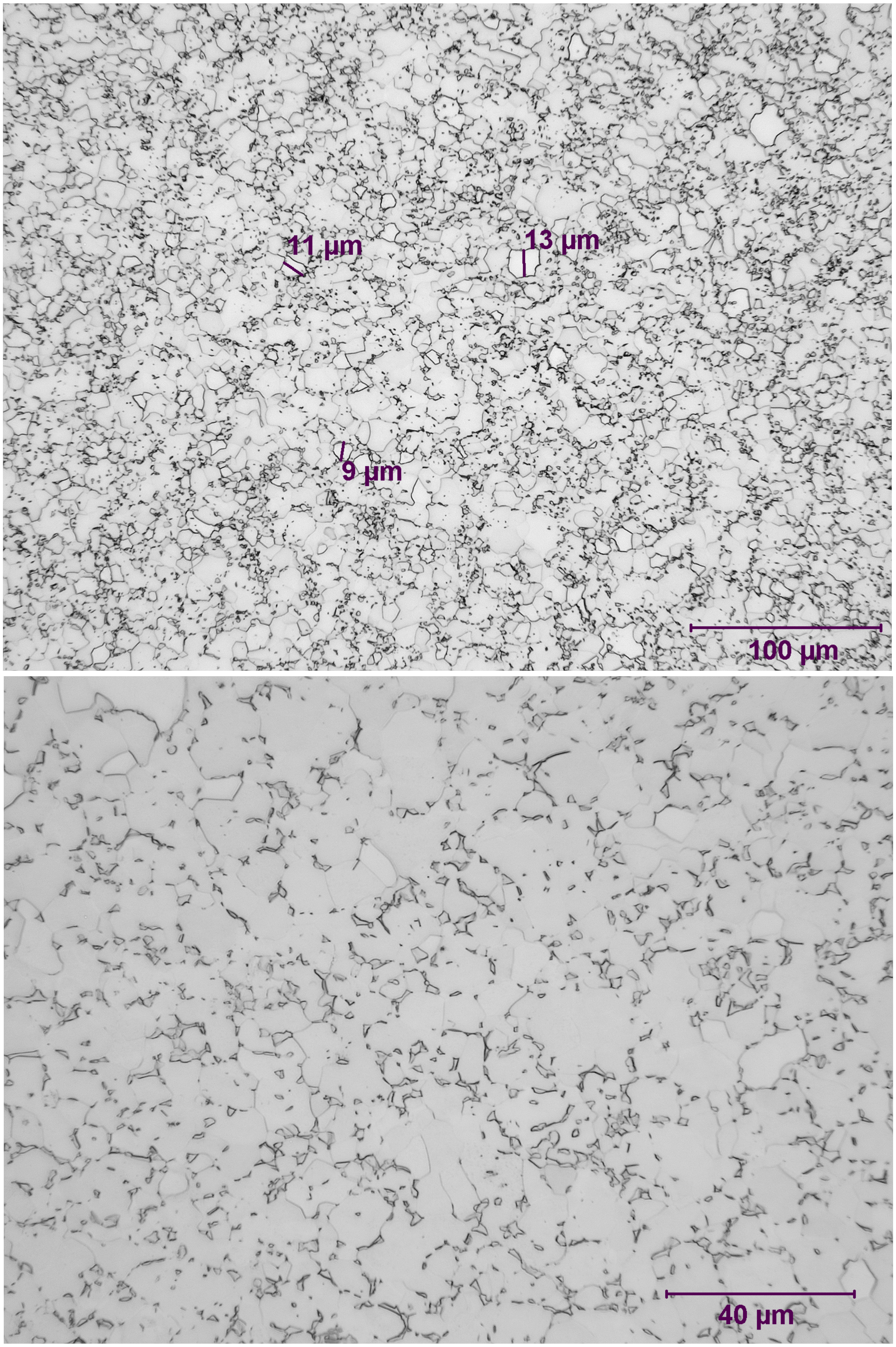
Young's moduli of VascoMax C-series steels are also sensitive to composition. The nominal composition of VascoMax C-350 steel is 18.5% Ni, 12% Co, 4.8% Mo, and 1.4% Ti, with balance of Fe. The Young's moduli of C-200 to C-350 steels increase from 181 to 200 GPa, respectively, as the Co, Mo and Ti alloying elements increased. These values were determined from the peak maraged conditions [2].

The fracture surfaces of the SHT VascoMax C-350 specimens suggest that the steel is much more ductile than indicated by the elongation values. Figure 4 shows the typical fracture surface of the VascoMax specimen. The cross-sectional view of the specimen shows a substantial necking. Compared to the Ti64 alloy, the dimples are much deeper and have more ductile fracture appearance, indicative of ductile material failure.

In summary, both materials are uniquely different. They have many beneficial attributes that make both materials highly attractive. The selection of the material should be determined by the specified property requirements of the applications.

References

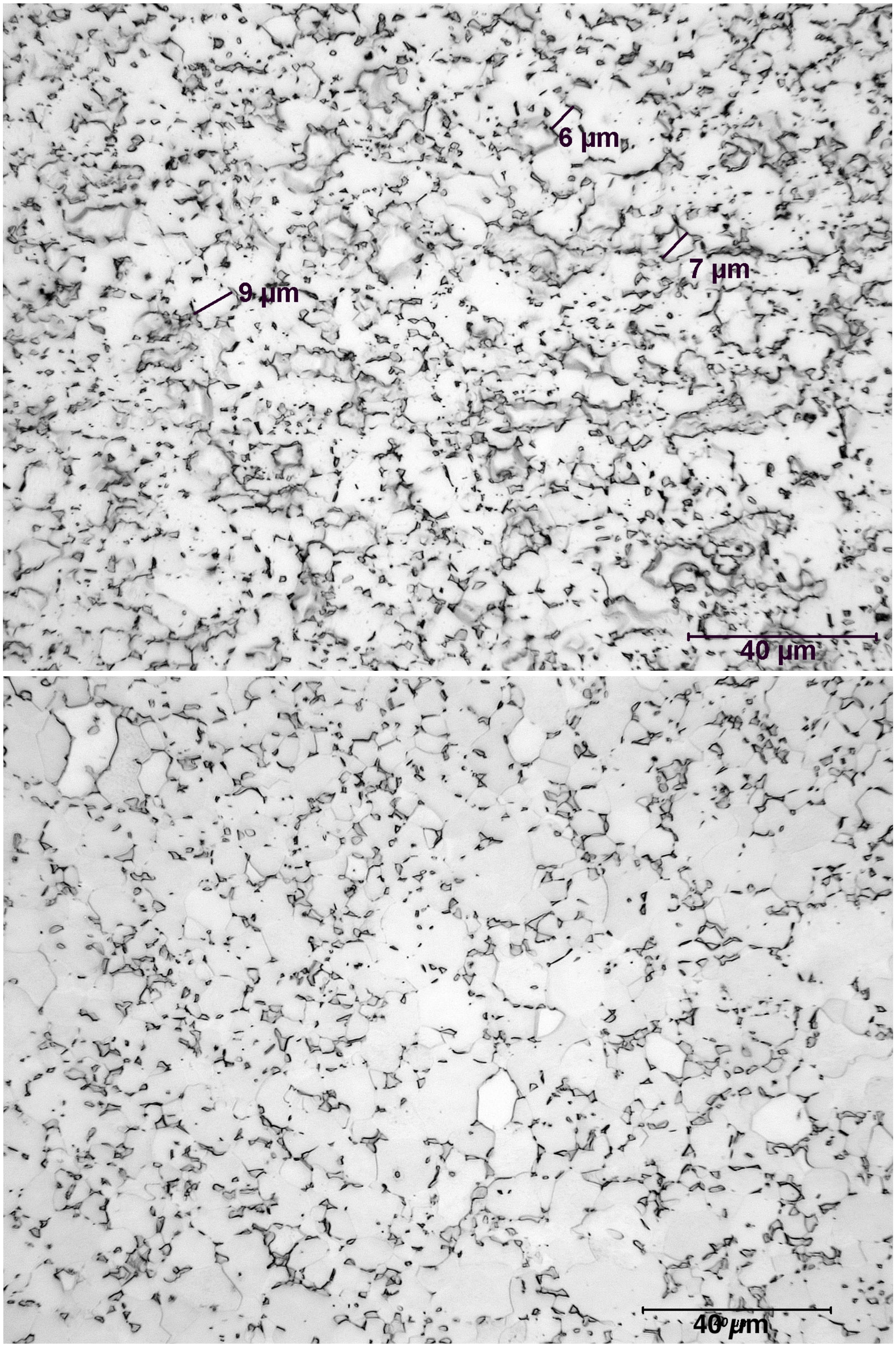
1. Ti Alloys Handbook, ASM, 1994. 495.
2. Allvac, technical datasheet.



a.

b.

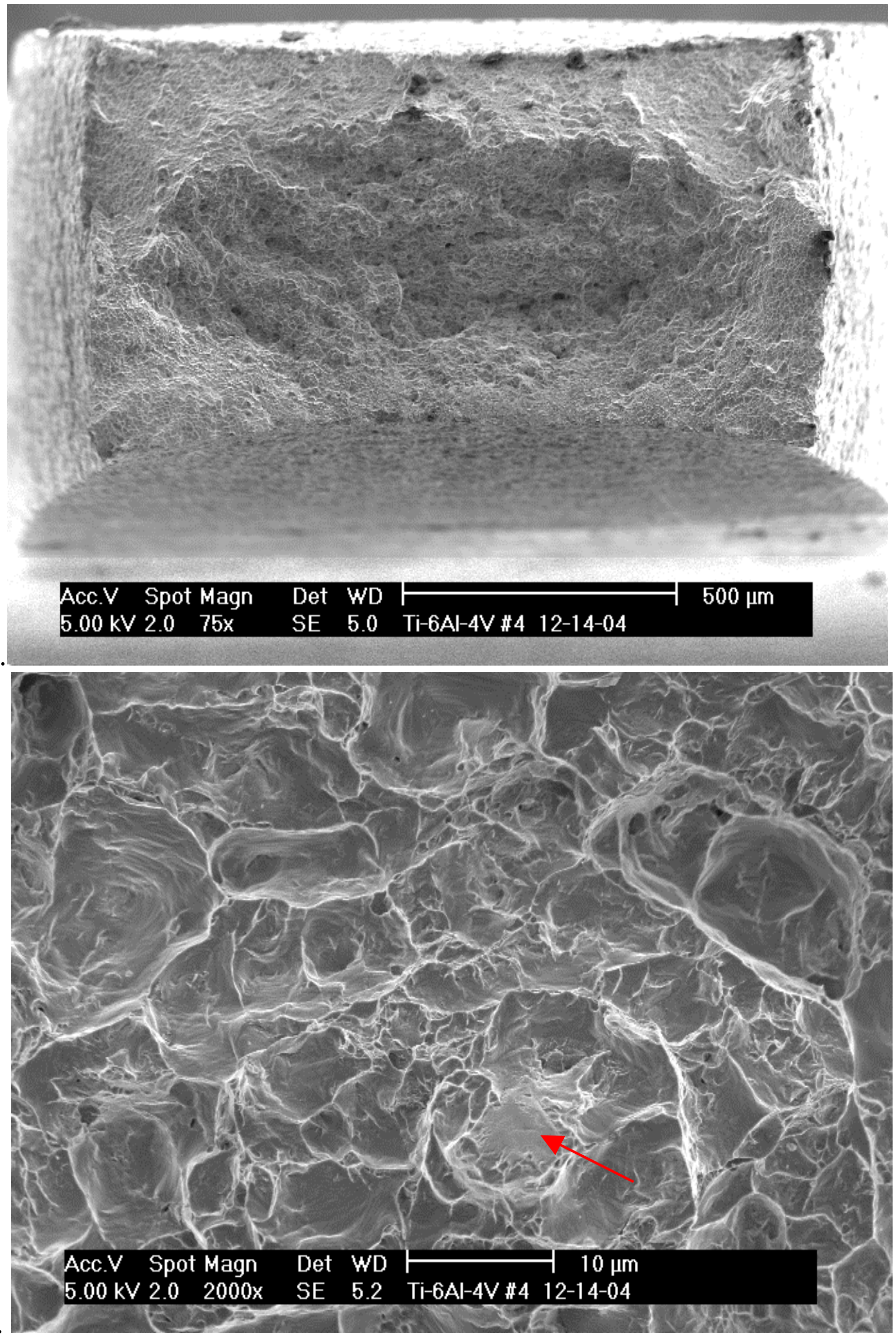
Figure 1. Optical micrographs of SHT and air-cooled Ti-64 alloy sheet from flat surface showing 10µm sized, equiaxed grains.



a.

b.

Figure 2. Optical micrographs of SHT and air-cooled Ti-64 alloy sheet from through thickness showing 8 µm sized, equiaxed grains.



a.

b.

Figure 3. SEM fracture surfaces of SHT Ti64 specimen, displaying ductile dimple failure; a) cross-sectional area overview, and b) size of the dimples are equivalent to the grain size and sheared surfaces, indicated by the arrow.

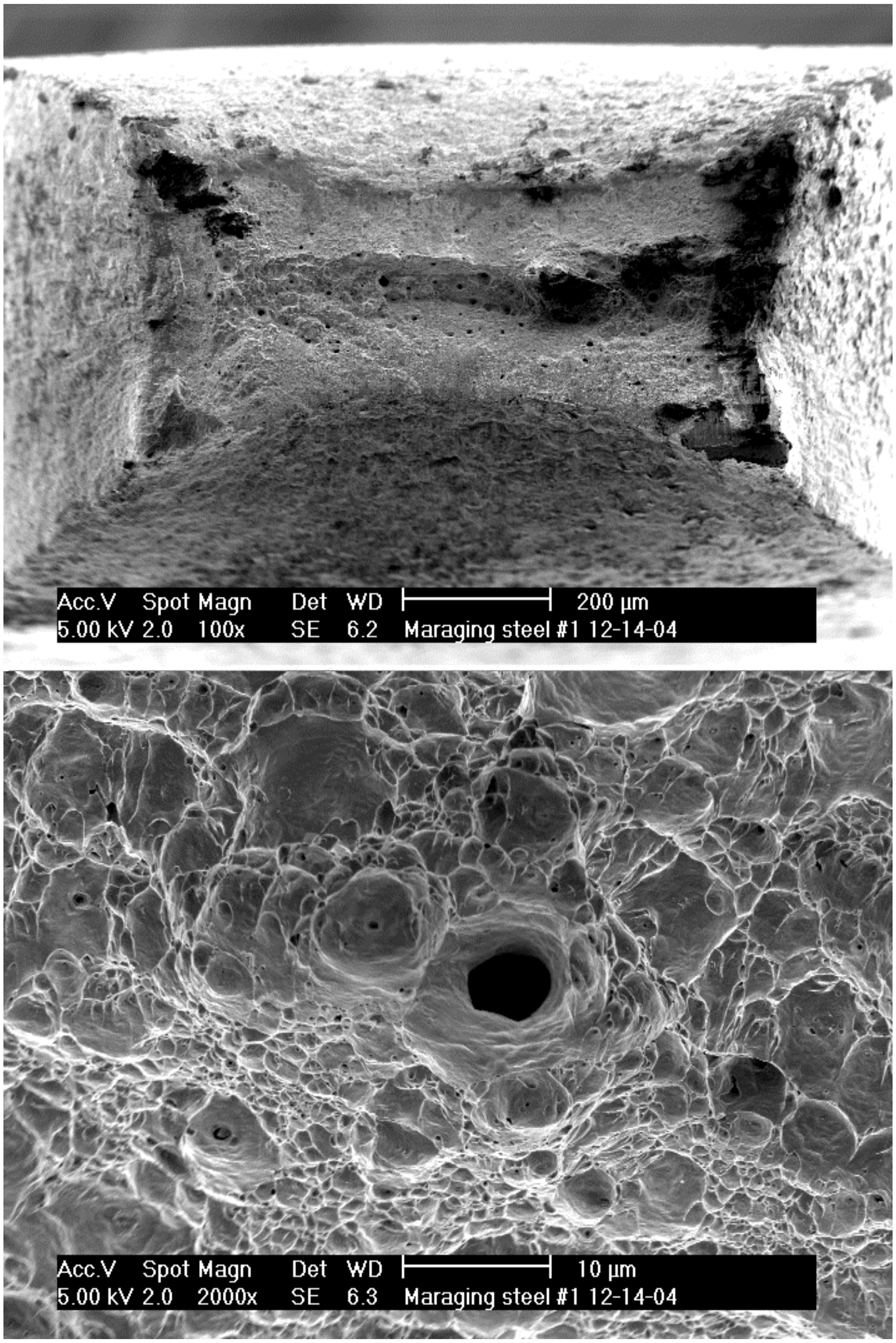


Figure 4. SEM fracture surface of SHT VascoMax C-350 steel displaying highly ductile fracture; a) cross-sectional area overview showing considerable reduction, and b) deep dimple formation.

Appendix 1: Tensile Properties of Annealed Ti-6Al-4V and Vascomax 350 Alloys

Mail Station L-342
Ext: 2-8954
Email: leblanc2@llnl.gov

December 15, 2004

ETR/WO #M0501465

To: Anne Sunwoo

From: Mary LeBlanc

Subject: Tensile tests of Ti-6Al-4V and Vascomax 350 miniature samples

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Per your request, tensile tests of four miniature samples of Ti-6Al-4V and two of Vascomax 350 were conducted at room temperature at a strain rate of 10-3/s (quasi-static).

Test setup

Tests were performed in an Instron1127 load frame using miniature wedge-type grips with ball-loading ends (Fig 1). Load was measured with the Instron 50kip load cell (5kN range). Deflection measurements were made with two 12.7mm (0.5") gage length MTS extensometers that have been specially modified to accommodate a sample gage length of 5.08mm (0.2"). A linear stage translation fixture was used to carefully attach the extensometers to the sample without damage. The load and deflection data were recorded with a Nicolet Vision system. Photographs of the setup are shown in Figs 2 and 3.

Note that the Instron 1127 load cell was calibrated on 8/25/04. The accuracy of the cell in the 5kN range is less than 0.2%. The extensometers were calibrated with a Boeckeler digital micrometer (S/N 31926).

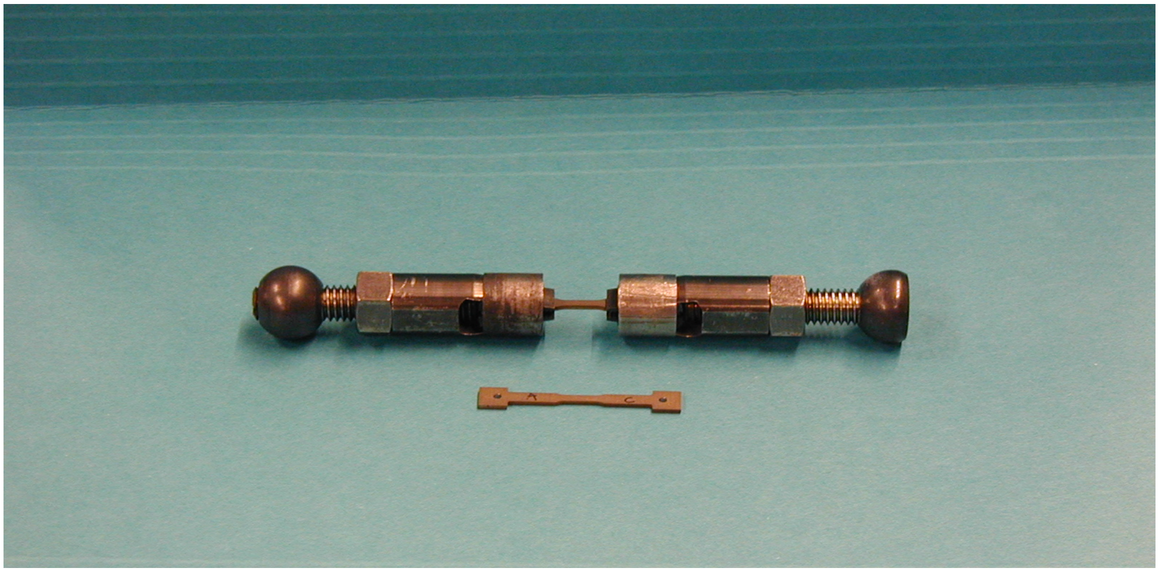

Figure 1. Miniature Ti-6Al-4V test sample and ball-end wedge-grips.

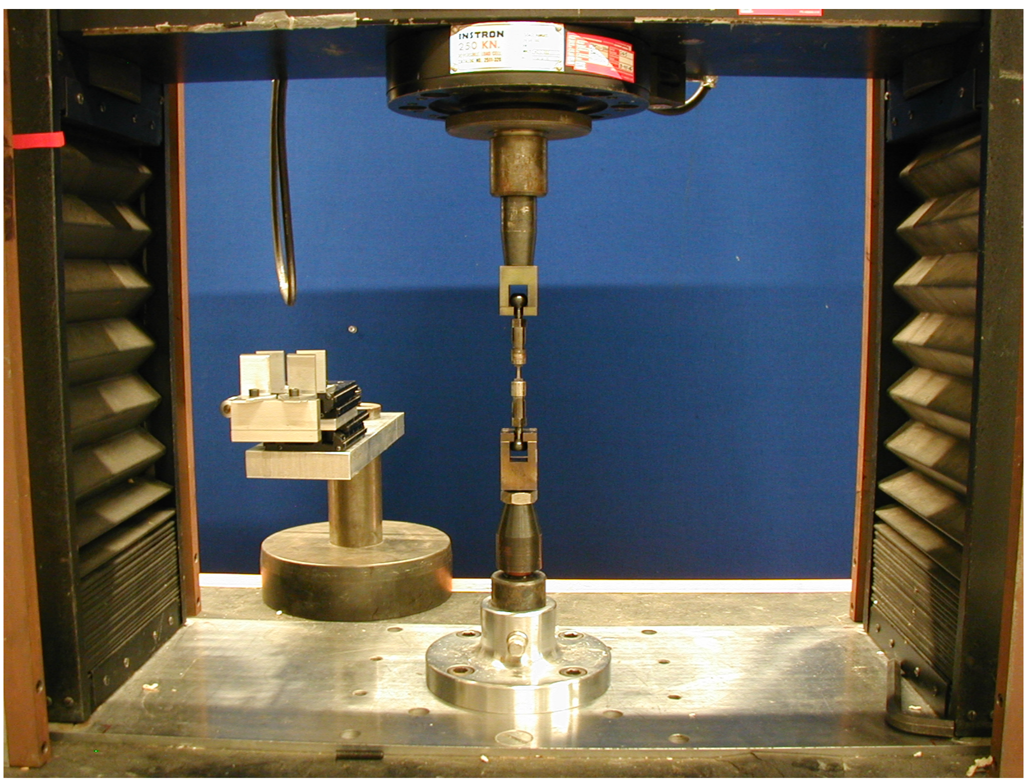

Figure 2. Ti-6Al-4V test sample and ball-end wedge-grips mounted in Instron 1127 load frame.

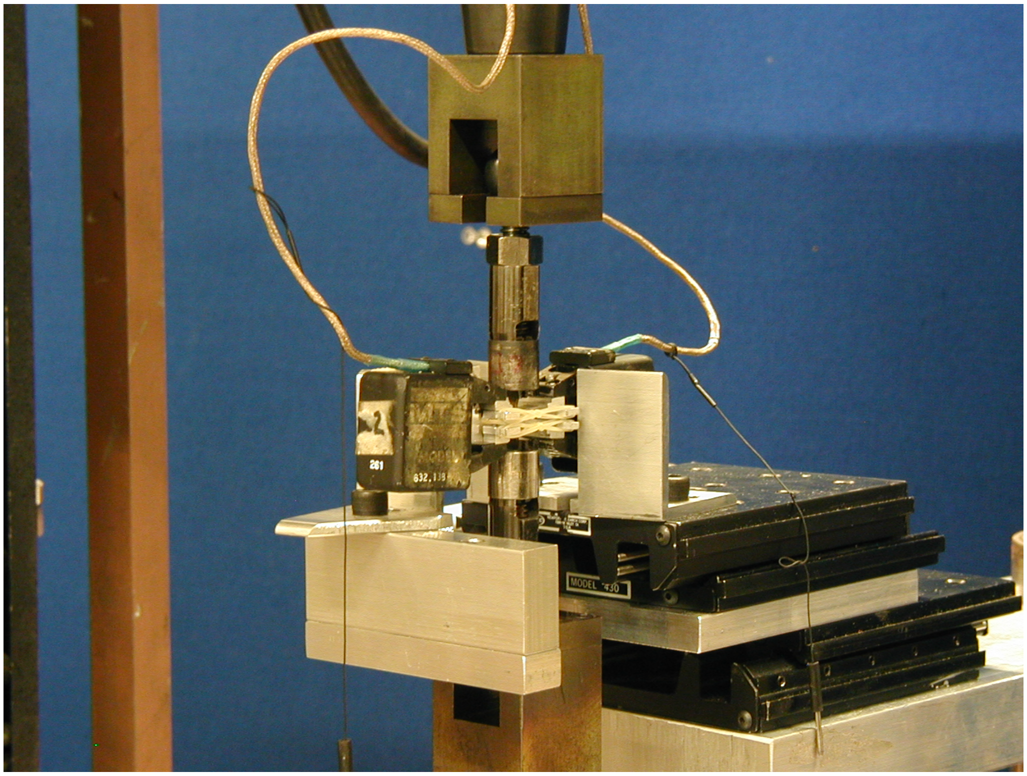

Figure 3. Ti-6Al-4V test sample and ball-end wedge-grips mounted in Instron 1127 load frame. Extensometers are attached to the sample.

Test samples
Sample measurements are given in Table 1. Holes 1.59mm (1/16”) in diameter were drilled in the grip area of the sample ends to accommodate the grips. Titanium samples #1 and #2 were tested in the “as-received” condition. Titanium samples #3 and #4 were polished with 30um and 11um abrasive in the gage area to remove the brass and other residue from the EDM fabrication process. Dimensions for samples #3 and #4 are given before and after polishing. The resulting difference in appearance of the sample sides and face due to polishing is illustrated in Figure 4.

The Vascomax 350 samples were not of uniform geometry. Although one side of each sample was flat, the other was tapered such that approximately one quarter of the sample was thinner than the rest. This tapered region extended into the gage section of the sample. In order to accurately grip and load the samples it was necessary to lap the samples until the gage section was uniform and fabricate stainless shims for the tapered area (Figures 5 and 6). The sample sides were then polished to remove EDM residue. Vascomax sample #1 had a mark on the face and side of unknown character (Figure 7). The sample failed at the mark area.

Table 1. Sample measurements

Sample ID	Ti #1	Ti #2	Ti #3	Ti #4	V #1	V #2
Thickness as rec (in)	0.0430	0.0426	0.0427	0.0426	na	na
Thickness after Polish (in)	na	na	0.04230	0.04220	0.03395	0.03475
Width as rec (in)	0.0785	0.0790	0.0785	0.0787	na	na
Width after polish (in)	na	na	0.07715	0.07705	0.05890	0.05890
Area as rec (in^2) x 10^{-3}	3.376	3.365	3.352	3.353	na	na
Area as polished (in^2) x 10^{-3}	na	na	3.263	3.252	2.000	2.047

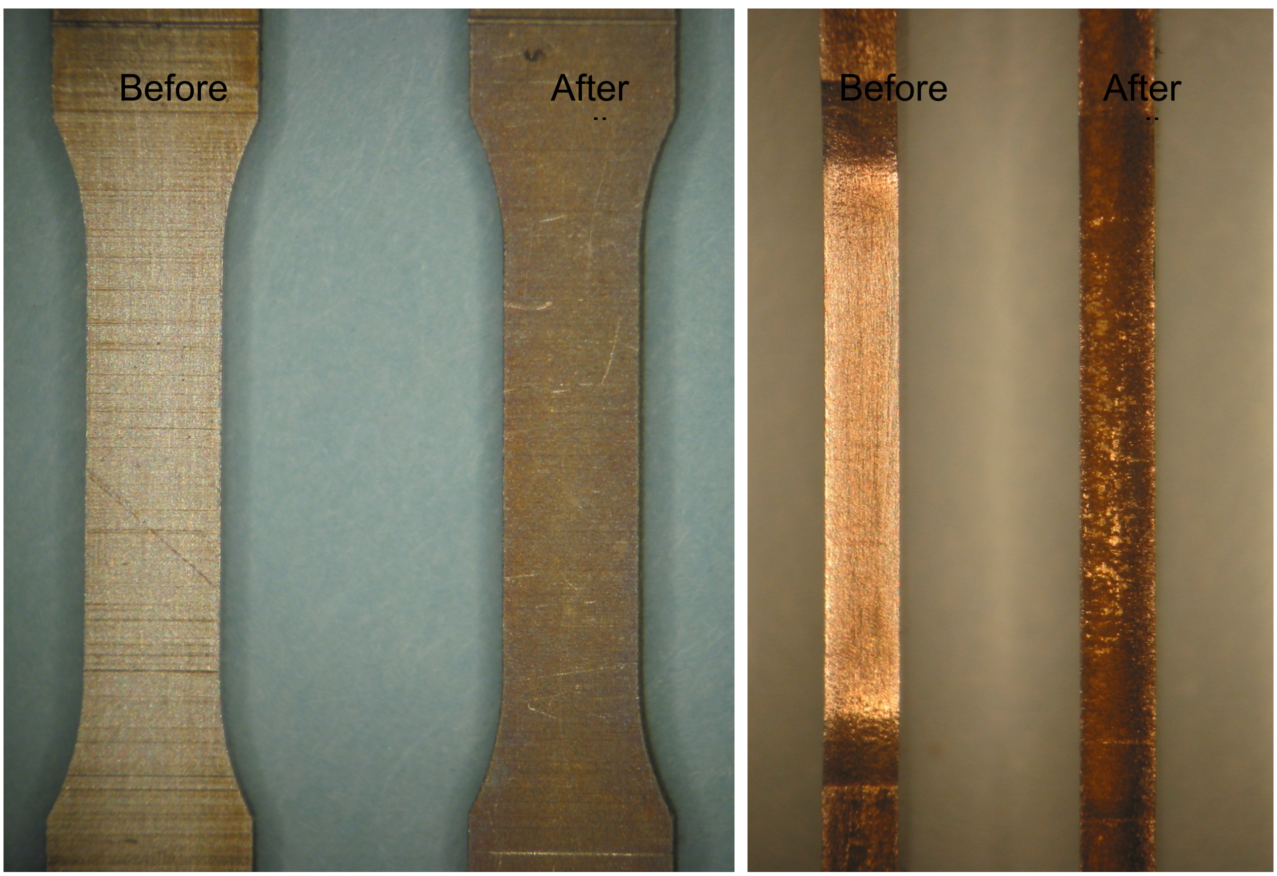

Figure 4. Surfaces of titanium samples before and after polishing.

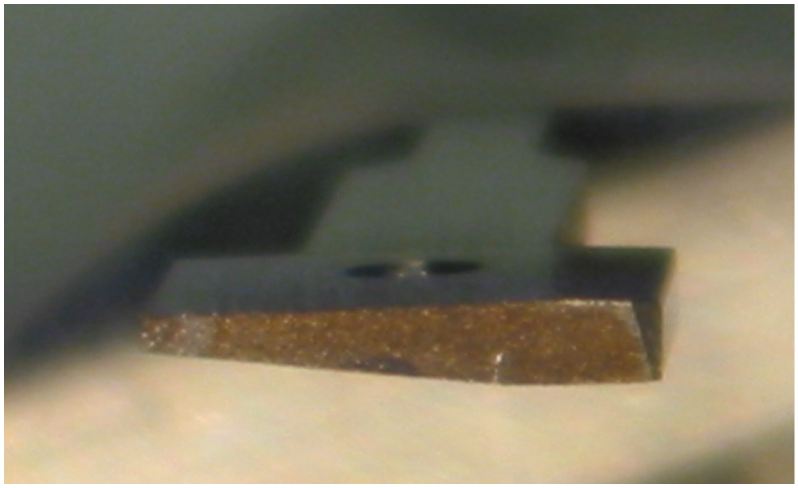

Figure 5. End of grip section in Vascomax 350 sample showing unevenness.

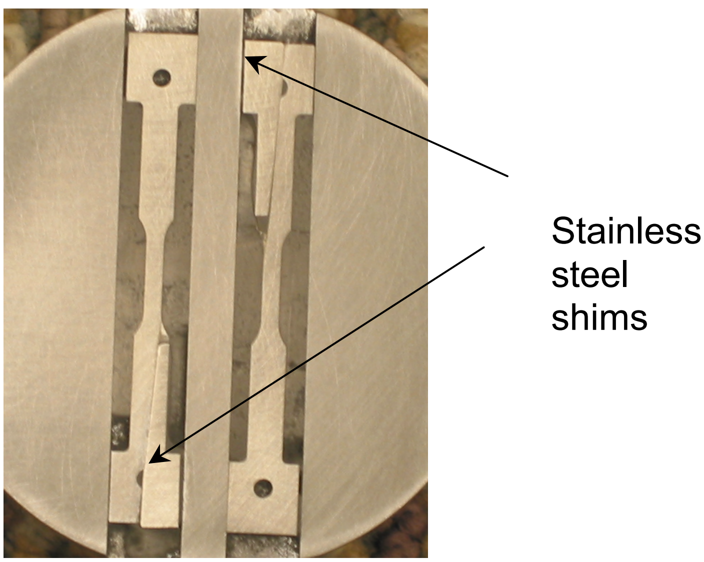

Figure 6. Vascomax samples lapped flat with shims glued to tapered region.

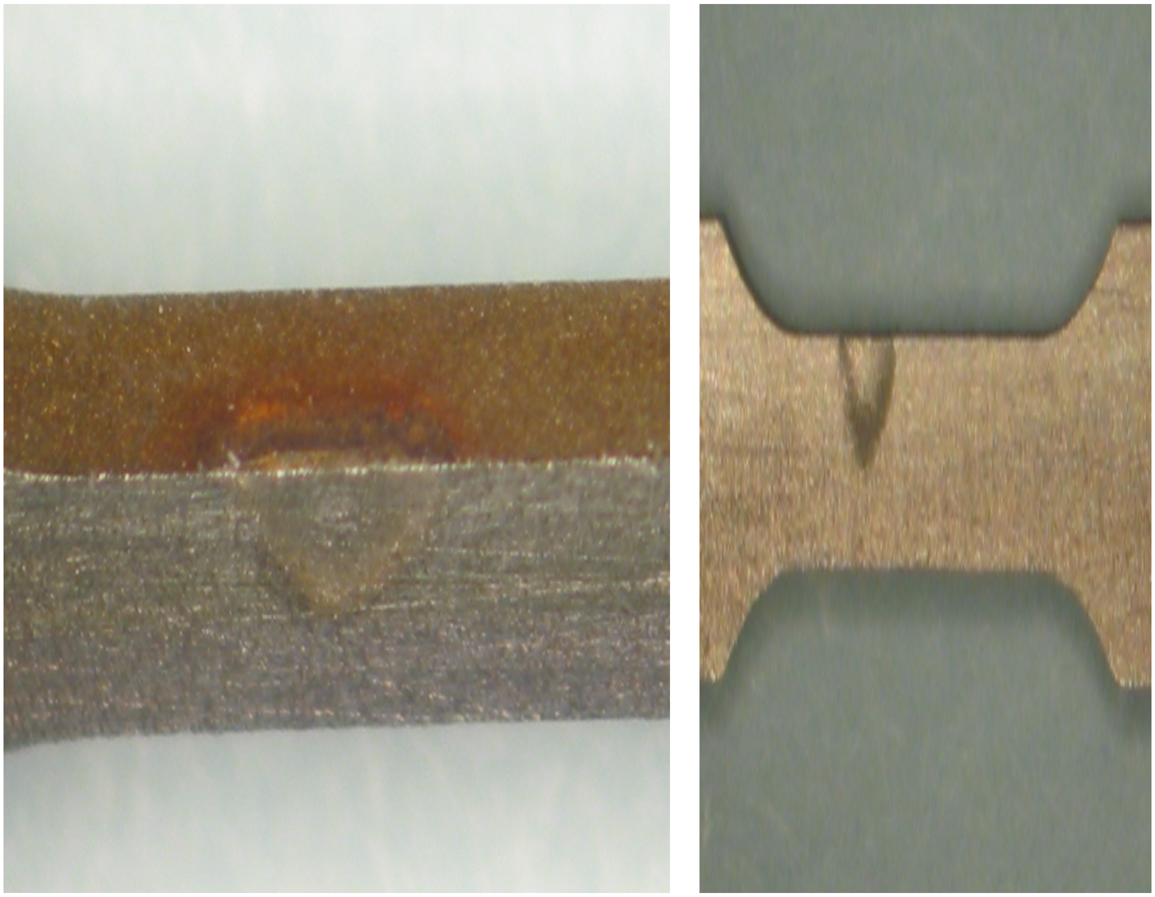

Figure 7. Mark of unknown character on Vascomax sample #1.

Test results
The Engineering stress-strain curves for the Ti-6Al-4V sample and Vascomax 350 samples are shown in Figures 8 and 9. The curves end upon failure of the sample.

Engineering stress was calculated as the applied load divided by the original cross-sectional area of the test sample. The area of Ti-6Al-4V samples 1 and 2 may be inaccurate (too large) due to the residual EDM layer of the sample surfaces. The remaining two Ti-6Al-4V samples and the Vascomax samples were polished to remove the EDM layer.

Engineering strain was calculated as the extensometer displacement divided by the original gage length. The actual gage length as placed on the specimen (different than the "pin-in" length) was used in each case. The curves below show the average of the two extensometers.

Measured values for Young's modulus, yield stress, ultimate stress, strain to failure and reduction of area are given in Table 2. It should be noted that the sample size and design are not appropriate for the accurate measurement of Young's modulus and that the reported modulus values do not meet ASTM requirements for accuracy.

For comparison, the manufactures' nominal annealed tensile property values are given in Table 3. Given the differences in specimen geometry and strain rate, the present UTS results are comparable to the reported values.

Table 2. Measured values of Ti64 alloy and VascoMax C-350 steel.

Sample ID	Young's modulus (GPa)	0.2% offset yield strength (MPa)	Ultimate tensile strength (MPa)	Strain to failure (%)	Reduction of area (%)
Ti-6Al-4V #1	106	867*	915*	26.7	55.6
Ti-6Al-4V #2	106	850*	900*	26.4	55.7
Ti-6Al-4V #3	101	863	925	26.4	54.6
Ti-6Al-4V #4	106	873	928	27.1	54.4
Vascomax 350 #1	157	1068	1176	16.0	76.8
Vascomax 350 #2	166	1033	1157	17.0	79. 6

* Sample tested in the as-received condition (not polished to remove EDM layer). Area may be artificially high. Stress values may be artificially low.
** On polished metallographic samples using 100gf load.
*** From manufacture's technical datasheet.

Table 3. Nominal annealed tensile properties from manufacture's technical datasheet.

Sample ID	Young's modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction of area (%)
ELI Ti-6Al-4V #1 (L)	-	904	927	12.5	-
ELI Ti-6Al-4V #2 (L)	-	920	949	12.6	-
ELI Ti-6Al-4V #1 (T)	-	885	932	11.5	-
ELI Ti-6Al-4V #2 (T)	-	923	975	13	-
Vascomax 350	200*	827	1138	18.0	70

*Heat treatment condition unknown.

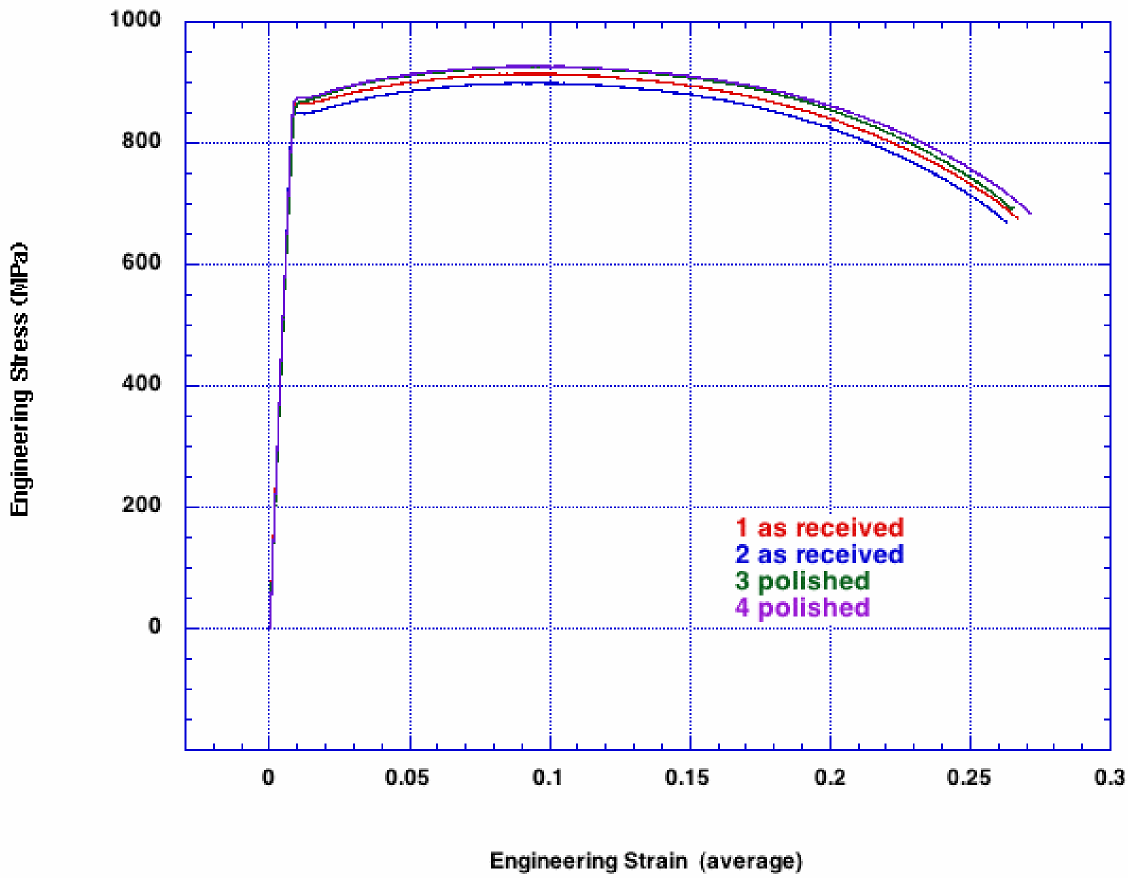

Figure 8. Engineering stress-strain curves for Ti-6Al-4V samples tested at 10^{-3}/sec. Samples 1 and 2 were tested in "as-received" condition. The data for samples 1 and 2 are artificially low due to inaccuracies in the measurement of the sample gage section (EDM residue).

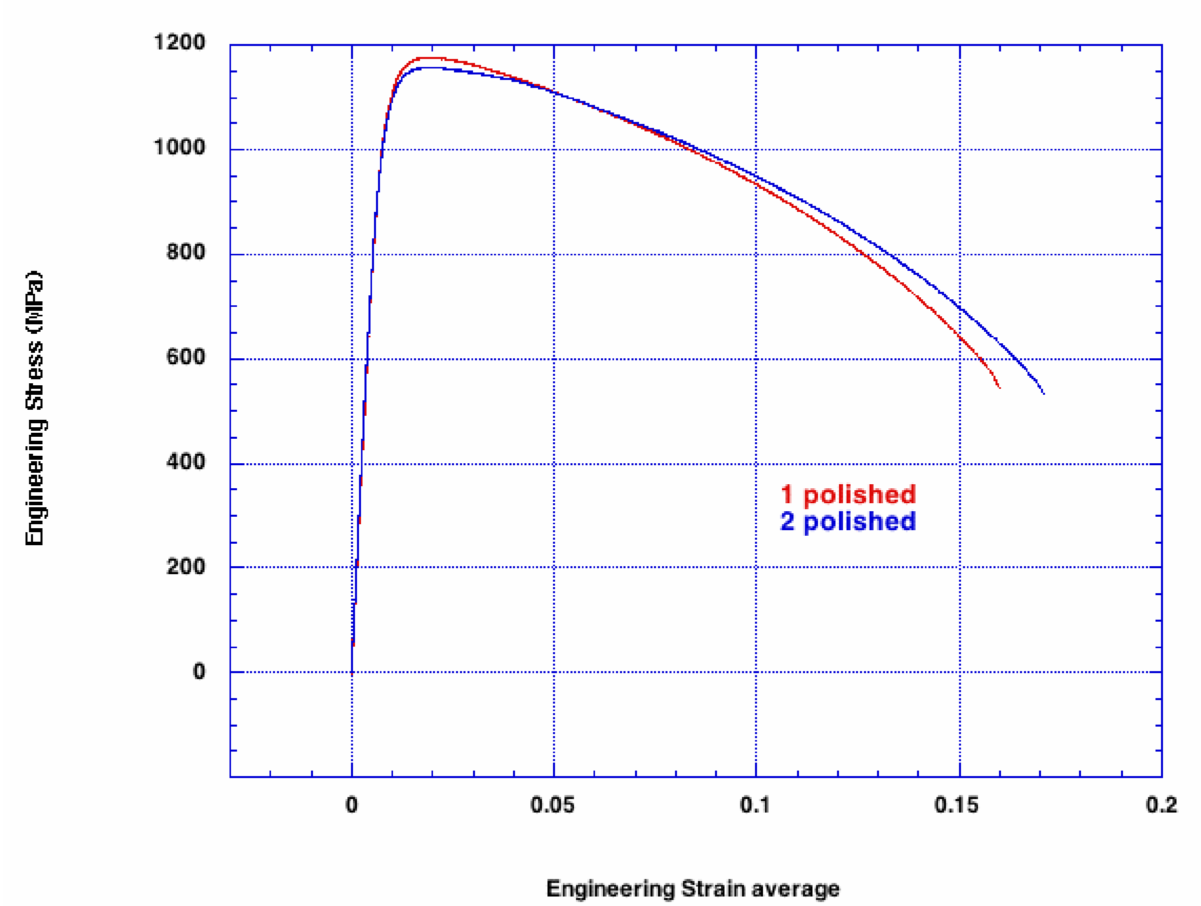

Figure 9. Engineering stress-strain curves for Vascomax 350 samples tested at 10^{-3}/ sec.

APPENDIX I Calibration information

The Instron 1127 load cell was calibrated on 8/25/04. The accuracy of the cell in the 5kN range is >0.2%. The extensometers were calibrated with a Boeckeler digital micrometer (S/N 31926).

APPENDIX 2: Review of Irradiated Tensile Data from BNL

The effect of the irradiation induced damage on the tensile properties of the Ti-6%Al-4%V alloy is investigated. After reviewing the population of the test data from BNL, the following observations are made. Assuming that all the test conditions were the same. I was only able to determine the ultimate tensile strength (UTS), fracture strength (FS), and corresponding strain.

As the amount of irradiation dosage increased, the UTS and FS values increased, and the rate of hardening increased. The UTS values were achieved at an earlier strain, and correspondingly the strain to failure occurred earlier.

In addition to the specimen identified as TiAlV-03, there appears to be others that exhibited the similar strength and strain values, Ti-10x, Ti 10-Nl, Ti 10-Nl 1, Ti 47-Nl, Ti-02. On the other hand, Ti-07 displayed extremely low strength and strain values. It had no description as to the amount of irradiation dosage the specimen may have received to lose its strengthening mechanisms. The irradiation and test conditions should be reviewed for the Ti-07 specimen.

Tables 1 and 2 provide the UTS, FS and strain values in the numbered sequence and regrouped with similar data, respectively. Although there is a definite loss of ductility with the increased irradiation, the alloy continued to display the resistance to fracture by deforming beyond the onset of plastic instability. The characterization of the fracture surfaces is needed to determine whether the alloy is failing in a ductile manner.

The damage mechanisms could be the atomic level, such as the displacement of atoms, or a phase change. The deformation mechanism of the alloy is predominantly twinning. With the amount of hardening seen in the alloy with the irradiation, it may have changed to a dislocation movement. The irradiation damage mechanisms need to be further studied.

Table 1. Tensile data from BNL

Specimen #	UTS. MPa	Strain at UTS, %	FS, MPa	Fracture Strain, %	Amount of irradiation
BNL					
TiAlV-03	986.2	20.4-22.75	735	33.9	0 μCi
Ti-04	1015.5	17.08-18.1	771	30	
Ti-05	1041	14.4-14.67	791	27	
Ti-06	1057	14.5-14.75	850	23.5	
Ti-07	721	16.5-16.67	579	24. 7	
Ti-08	1050	14.4-14.67	828	25	
Ti-09	1023.5	15.8-16.17	780	29.8	
Ti-10x	988	15.9-18.08	749	31	
Ti -11	1009	16.4	759	30.4	
Ti-12	1028	14.7-14.9	806	28	
Ti-13	1107	14.67-15	900	23.1	16.97 μCi
Ti-14	1086	15.417	903.3	23	
Ti-15	1062.3	15.417	845	25	
Ti-16	1052.5	14.58	792.5	29.3	3.76 μCi
Ti-17	982.4	17.33-17.92	746.8	31.9	
Ti-18	1031.2	16.5-18.08	786	30.4	1.37 μCi
Ti-19	1045.3	14.8-15	806.1	27.3	
Ti-20	1082.3	16.167	865.1	24. 7	
Ti-21	1087	16.25	812.7	24.25	
Ti-22	1064.7	14.83-15	830.3	25.1	
Ti 10-Ni	960	20.92-21.25	718	35.5	
Ti 02-Ni 1	946	22-23	717	35	
Ti 47-Ni	954	21.8-23.5	715	36	
Ti-02 Nl	946.4	22-23	717	35.4	

Table 2. Regrouped test data from BNL.

Specimen #	UTS. MPa	Strain at UTS, %	Fracture Stress, MPa	Fracture Strain, %	Amount of Irradiation
BNL					
TiAlV-03	986	20.42-22.75	735	33.92	0 μCi
Ti 10-Ni	960	20.92-21.25	718	35.5	
Ti 02-Ni 1	946	22-23	717	35	
Ti 47-Ni	954	21.8-23.5	715	36	
Ti-02 Nl	946	22-23	717	35.4	
Ti-18	1031	16.5-18.08	786	30.42	1.37 μCi
Ti-04	1016	17.08-18.08	771	30	
Ti -11	1009	16.4	759	30.4	
Ti-16	1053	14.58	792.5	29.33	3.76 μCi
Ti-15	1062	15.417	845	25	
Ti-19	1045	14.8-15	806	27.25	
Ti-20	1082	16.167	865	24.67	
Ti-21	1087	16.25	813	24.25	
Ti-22	1065	14.83-15	830	25.08	
Ti-12	1028	14.7-14.9	806	28	
Ti-08	1050	14.42-14.67	828	25	
Ti-09	1024	15.8-16.17	780	29.8	
Ti-13	1107	14.67-15	900	23.1	16.97 μCi
Ti-07	**721**	**16.5-16.67**	**579**	**24.67**	**?**